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Major Dan Johnstone
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August 18, 1999

Maj. Johnstone,

Enclosed is a copy of my final report for the grant *DURIP 98-99 Molecular Beam Epitaxial Growth and In Situ Characterization of Phase Separated Optoelectronic Semiconductors*, grant number F49620-98-1-0335.

If you require any additional documentation or information, please don't hesitate to contact me.

Thank you for your assistance. I look forward to seeing you at the program review.

Sincerely,

Joanna Mirecki Millunchick
Assistant Professor

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This proposal requested funding to procure a Molecular Beam Epitaxy (MBE) chamber with extensive in situ diagnostic capabilities to study phase separation of III-V semiconductor alloys during epitaxial growth. An EPI930 Molecular Beam Epitaxy system was purchased from EPIMBE Products Group and installed in September of 1998, and is fully operational. This piece of equipment has facilitated several new research propgrams in t;he area of morphological and compositional evolution in III-V semiconductor thin films.

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DURIP 98-99: Molecular Beam Epitaxial Growth and In Situ Characterization of Phase Separated Optoelectronic Semiconductors

Final Report

Grant Number F49620-98-1-0335

March 1 1998- February 28 1999

Total Amount $449,000

Principal Investigator:

Joanna Mirecki Millunchick

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University of Michigan

Ann Arbor MI 48109

Executive Summary

This proposal requested funding to procure a Molecular Beam Epitaxy (MBE) chamber with extensive in situ diagnostic capabilities to study phase separation of III-V semiconductor alloys during epitaxial growth. An EPI930 Molecular Beam Epitaxy system was purchased from EPIMBE Products Group and installed in September of 1998, and is fully operational. This piece of equipment has facilitated several new research programs in the area of morphological and compositional evolution in III-V semiconductor thin films.

General Description of the MBE Chamber

This grant provided funding to procure a Molecular Beam Epitaxy (MBE) chamber with extensive in situ diagnostic capabilities to study phase separation of III-V semiconductor alloys during epitaxial growth. The function of the MBE system is to serve as both a growth tool and a characterization platform. Therefore, the design of the chamber must be flexible enough to accept a number of diagnostic and materials configurations, yet maintain the highest standards for optoelectronic-device growth. In order to fulfil these needs, an EPI930 model growth system configured to grow III-V compound semiconductors on 3" wafers was procured. It was installed in September of 1998 and is fully operational. The system is configured in the following manner:

- **Introduction chamber**: designed for quick loading of wafers. This chamber is pumped by a turbopump backed by a dry mechanical pump
- **Buffer Chamber:** designed to store wafer in vacuum. This chamber will be upgraded in the future to include an outgassing station. This chamber is pumped by a 200 l/s ion pump.
- **Growth Chamber:** This chamber is pumped by a 400 l/s ion pump. It is designed specifically for the growth of III-V semiconductor films and has the following features:
    - 9 port source flange
    - Group III sources: Al, Ga, In
    - Valved cracker sources for Group V: As, Sb
    - Dopant source: Be

- kSpace Associates RHEED data acquisition system
- Beam flux monitor
- Stanford Research 1-300 amu RGA
- Biasable sample manipulator
- Molly Control software
- Additional ports for:
    - Ellipsometry
    - Reflection High Energy Electron Diffraction
    - Pyrometry
    - 2 Additional cryopumps

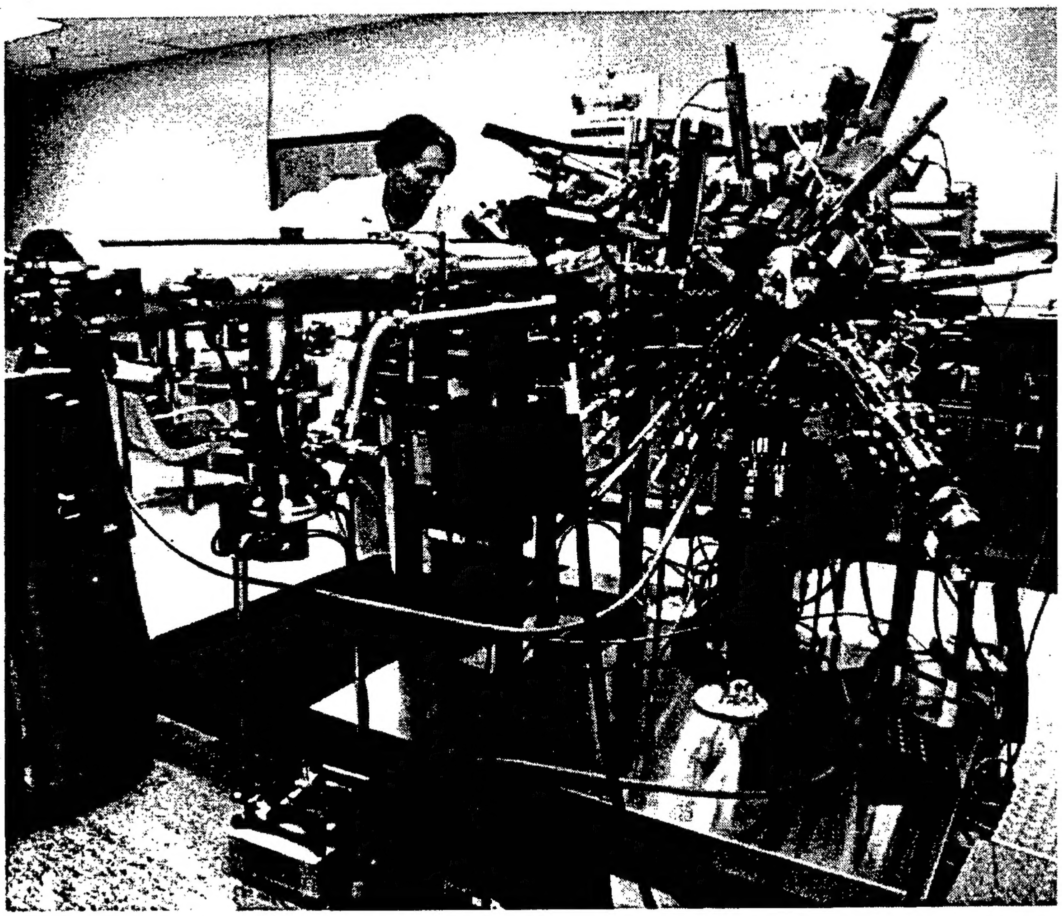

Figure 1: EP1930 Molecular Beam Epitaxy chamber installed at the University of Michigan

Associated Costs

The total cost of this system was $449,000. $200,000 of that total came from University cost sharing, and the balance from this grant. Not all the necessary components could be purchased on this grant alone. Thus additional equipment was acquired using other means of funding. They include:

- Ircon 3V Modline 3 pyrometer. Funding source: start up funds
- Staib 15 keV RHEED system. Funding source: *Acquisition of a Reflection High Energy Electron Diffraction (RHEED) System.* University of Michigan Office of the Vice President of Research Discretionary Funds.
- CTI Cryogenics CT8 Cryopump. Equipment donation from CTI Cryogenics.

Summary of Research Projects

The success of the semiconductor industry relies on the ability to obtain high quality thin films. However, some applications require the integration of dissimilar materials, which can lead to defects that degrade crystal quality. For example, it is well known that a film with a larger lattice spacing than the substrate upon which it is grown will form islands above some critical thickness of deposited material. Detailed understanding of this so-called 2D to 3D transition will have tremendous impact on such seemingly disparate issues as improved film quality and novel quantum-sized structures. Experiments have shown that discrete islands[1] or continuous surface undulations[2] can form without introducing defects. Subsequently, these phenomena have been applied in exciting and novel ways. For example, the formation of defect-free 3D islands has been utilized in quantum scale devices (where the dimensions are on the order of a few hundred angstroms). Also, surface undulations have been shown to be correlated to lateral composition modulation, yet another avenue to spontaneous quantum dimensional structures.

This equipment has facilitated a number of new research projects investigating the compositional and morphological evolution of III-V semiconductor thin films. The ultimate goal of this effort to is understand the mechanisms of morphological evolution and phase separation and how they interact. To this end, three distinct research projects have been initiated that study (i) morphological evolution in strained films (ii) alloy formation in mixed anion compound semiconductors, and (iii) lateral composition modulation. Three graduate students are currently working on these projects.

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[1] D. J. Eaglesham and M. Cerullo . "Dislocation-free Stranski-Krastanov growth of Ge on Si(100)." Physcial Review Letters 64 1943 (1990)

[2] R. J. Asaro and W. A. Tiller . "Interface morphology development during stress corrosion cracking: part I. via surface diffusion." Metall. Trans. 3 1789 (1972)

Morphological evolution in strained thin films

In spite of the recent activity in this area, a unified understanding of the 2D to 3D transition has yet to emerge. The experiments proposed here investigate the roughening process as a function of the lattice mismatch and the growth temperature in an effort to understand the 2D to 3D roughening transition. In this study, InGaAs is grown on different substrates for various growth conditions to determine their effect on the roughening transition. The substrates will be varied in order to study the effect of changing the relative mismatch without altering the chemistry of the film. Films of varying thickness have been grown and examined using Atomic Force Microscopy (AFM) to study morphological evolution. The growth temperature has also be varied to investigate role of kinetics in the roughening process. Transmission Electron Microscopy (TEM) will also be performed on selected samples to examine the defect structure within the films.

Funded Research:

- The effect of misfit on the morphology of strained semiconductor thin films. Rackham Spring/Summer Student Support Grant.
- Start up funds

Cognizant Graduate Student:

- Nehal Chokshi

Papers and presentations:

- N. Chokshi and J. Mirecki Millunchick, "A comparison of InGaAs surface morphology in compression and in tension," Submitted to *Applied Physics Letters*
- N. Chokshi and J. Mirecki Millunchick, "A comparison of InGaAs surface morphology in compression and in tension," presented at Fall Meeting Materials Research Society, December 1998, Boston MA

Alloy formation in mixed anion compound semiconductors

III-V semiconductor alloys are routinely used in sensors and emitters; however, their growth is not completely understood. For example, the formation of mixed anion alloys has been shown to have a complex dependence on the chemistry of the growing surface. This research project studies anion incorporation in (In,Ga,Al)AsSb alloys in

order to understand how the surface chemistry affects alloy formation. *In situ* and *ex situ* techniques along with a novel flux feedback scheme are being employed for characterization.

Funded research:

- Solid state chemistry of mixed anion semiconductor alloys. Petroleum Research Fund, American Chemical Society

Cognizant Graduate Student:

- Aruna Seshadri

Papers and presentations:

- A. Seshadri and J. Mirecki Millunchick, "Nucleation and growth of GaAsSb and InGaSb on InP substrates," in preparation

Lateral Composition Modulation

Infrared emitters and detectors for gas sensing and thermphotovoltaic applications would not be possible without high quality InGaAsSb semiconductor alloys. .However, this material has the unfortunate property of having a substantial miscibility gap. This results in compositional modulations across the layer that degrade device performance. Typically, device designers deal with this "problem" by developing techniques to obtain highly uniform material. However, *exploiting* spontaneous phase separation would revolutionize how these materials are used. For example, it would become possible to utilize composition modulation to form low dimensional structures such as quantum dots or wires. As a result, the density of states would increase, leading to such benefits as lower threshold currents, higher bandwidth, and better temperature stability in devices made out of these modulated materials. In order for spontaneous composition modulation to be applied in this way, basic parameters, such as modulation amplitude, wavelength, and profile need to be understood and precisely controlled.

This project examines the fundamental issues of composition modulation in general, and particularly in mixed anion (arsenide-antimonide) alloys. One of the primary objectives of this work is to determine how individual atoms incorporate along an undulated surface and develop lateral composition modulation. To this end, we will build

and install a Scanning Tunneling Microscope onto the growth system obtained by this grant. The significance of this work is that it will elucidate the mechanisms for lateral composition modulation and test current models. In addition, this program will expand our understanding of strained alloy growth in general. In addition, this work will for the first time demonstrate lateral composition modulations in mixed anion systems. We will study the microstructural evolution and correlate it to optoelectronic properties. We will also utilize this phenomenon in improved thermophotovoltaic devices.

Funded research:

- In situ and ex situ investigations of lateral composition modulation. Campus Executive Program, Sandia National Laboratory
- Nanometer-sized structure in compound semiconductor alloys. Rackham Faculty Grant, University of Michigan.
- The morphology and chemistry of lateral composition modulation. National Science Foundation. With Prof. B.G. Orr
- Nucleation and growth of arsenide-antimonide alloys: towards low dimensional structures. Basic Energy Sciences, Department of Energy. *Pending*
- Novel Material Architectures for Improved Infrared Emitters and Detectors. Air Force Office of Scientific Research. *Pending*

Cognizant Graduate Student:

- Catalina Dorin

Papers and presentations:

- J. Mirecki Millunchick, "Lateral composition modulation in III-AsSb compound semiconducotrs," in preparation